Military Vortices

D.A. Lovell*
QinetiQ, Farnborough, Hampshire GU14 0LX, UK

Summary

This paper briefly reviews the wide range of vortex flows encountered on military vehicles. Vortex flows are classified into those designed into a vehicle to improve performance, those which cannot be avoided and whose deleterious effects must be minimised, and those that were not expected to occur. Examples of vortex-flow effects on air and sea vehicles and in propulsion systems are cited to illustrate these categories. It is concluded that vortex flows are all-pervasive and can have major effects on the operation and performance of military vehicles. With the trend to increased diversity in shape for future vehicles it is deemed essential to continue to improve the knowledge and predictive capability for vortex flows.

Introduction

Over the past 25 years the NATO R&D community has met together on several occasions to consider the topic of vortex flows and high angle-of-attack aerodynamics. In 1978 the AGARD Fluid Dynamics panel held a Symposium on high angle-of-attack aerodynamics at Sandefjord (CP-247). This was followed by a series of Symposia and lecture series throughout the 1980s which addressed many aspects of vortex flows (ref NATO AGARD CPs 336, 342, 412, 432, 437 and 465). In 1990 a Symposium on Vortex Flow Aerodynamics was held at Scheveningen in the Netherlands. Several of the papers at this symposium reported work that demonstrated vortex flows could be harnessed to provide controlled flight at high angle of attack, e.g. the NASA F-18 HARV programme. It is significant to note (as pointed out by Masure during the Round-table discussion at this Symposium, ref CP-494) that there was no coverage of vortices associated with propellers, helicopter rotors or missiles at this Symposium.

Since the latter event there have been major changes in the research environment. Reductions continue to be made in defence spending and in consequence military research is being squeezed down to cover a far narrower breadth than previously. Today the leading-edge research for some of the most important technologies applied in military vehicles no longer comes from military research projects but from civil and consumer markets. This applies particularly to the computing and electronics fields. Thus software for man-in-the-loop simulation is driven by the needs of games technology, miniaturisation and efficiency of digital communications is driven by the needs of commercial telecommunications, and high-speed, high-performance computing is driven by multi-media needs of the consumer market. However many other aspects of military vehicle technology are unlikely to be developed for civil and consumer markets. A prime example is the technology required to define the shapes for military vehicles and their components that provide an acceptable trade-off between mission performance, survivability and cost. Many of the shapes that emerge to meet military requirements are not ones that would be considered for civilian transport vehicles or vehicle components, where high aerodynamic or hydrodynamic efficiency combined with minimum life-cycle cost is the design objective. One corollary of this is that (with a few notable exceptions such as Concorde) it is only military vehicles that are designed to make extensive use of vortex flows. This paper focuses on the influence of vortices on the design and operation of military vehicles.

A large number of the papers on vortex flow presented at previous NATO symposia covered research that was many years away from potential application. It is important to note that it can take 20 years or longer for research to lead to technology that is mature enough to be incorporated in a military vehicle

---

* Senior Technical Consultant, Air Vehicle Studies

Paper presented at the RTO AVT Symposium on "Advanced Flow Management: Part A – Vortex Flows and High Angle of Attack for Military Vehicles", held in Loen, Norway, 7-11 May 2001, and published in RTO-MP-069(I).

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **00 MAR 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Military Vortices**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NATO, Research and Technology Organisation, BP 25, 7 rue Ancelle, F-92201 Neuilly-Sur-Seine Cedex, France**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Initial considerations

While wishing to avoid mathematical details, it is necessary to refer to some basic concepts. The following introduces the subject, but is not entirely rigorous. We need first to consider vorticity, which is a measure of the strength of rotation or swirl in a flow. Mathematically vorticity, ω, is defined as:

$$\omega = \text{curl } V$$

where V is the velocity vector. This can be derived by considering the circulation about an infinitesimally small flow element. If we assume that vorticity is concentrated along lines or infinitesimally thin "sheets", which is not strictly true in real flows because the fluid viscosity dissipates and spreads the vorticity, then the velocity induced by the vortex at a point in the surrounding field is inversely proportional to the normal distance of the point from the vortex.

In general vorticity is generated from surfaces immersed in a moving fluid, though it may also be generated by curved shock waves. In both cases the presence of vorticity may lead to areas of separated flow region downstream. Two broad categories of separated flow may be distinguished:

- "Disorderly" separations, which include rotational flow but are comprised of a spectrum of sizes of unrelated vortex elements. The flow over the top surface of a wing with low sweep forms this type of separation when it stalls.
- "Orderly", vortex-dominated, separations that typically comprise a single large-scale vortex, possibly with related smaller-scale vortices. Flows from wing tips and from the leading edges of highly swept wings are examples of this type of separation.

The latter type of orderly behaviour can persist for a considerable distance downstream of the vehicle but eventually breaks down. The core of the vortex, where the vorticity is concentrated, bursts and forms a region of unsteady flow having large velocity perturbations. If the vortex is not in free air but is subjected to a pressure field from a neighbouring body this breakdown can be precipitated earlier.

In planning this paper, the first intention was to address "Military Vorticity" and cover the whole gamut of flow scale from sub-boundary layer vorticity up to the large-scale vortices. This would have entailed covering the whole field of turbulence, which is not appropriate for the present symposium. But it is necessary to point out that vortex structures within the layer of fluid adjacent to the surface of a vehicle play a fundamental role in the mixing of fluid across a boundary layer of turbulent flow. This mixing effect does produces considerably more friction on the surface than a laminar flow (where the fluid laminae slide over one another), however it does make the flow far more tolerant of the detailed shaping of vehicle "features". The flow can thus, in principle, be designed to remain largely attached to the surface of a vehicle for a greater part of the operating envelope, with consequent benefits in vehicle drag and mission performance.

Whilst briefly considering small-scale vortical flows, it should also be noted that the flow control methods being exploited by MEMS devices (Micro-electro-mechanical systems) rely in many cases on the manipulation of small-scale vortices to provide favourable mixing effects. By appropriate design and siting of MEMS very local effects on the flow can be made to provoke large-scale changes in the flow structure and, for example, control the conditions at which the flow separates. This specialist area will not be considered further in the present paper but results from current research indicate that there should be large potential benefits for military capability to be derived from this technology when it reaches maturity. The remainder of the paper will therefore consider larger-scale separated flows of a vortical nature, which may be steady or time dependent. For the purpose of the present paper vortex flows may be categorised into three types:

- those which are designed into the vehicle or component to improve system performance
- those which are anticipated but must whose effects must be ameliorated
- those which were unforeseen or have unforeseen consequences

These will be considered in turn, with examples drawn from full-scale vehicles and components.

Vortex flows to achieve military effectiveness

Lift

The most fundamental aspect here is that a large quantity of lift must be generated to balance the weight of the vehicle. Even with a buoyant air or sea vehicle, lift will be required to provide a force for manoeuvring the vehicle normal to the direction of motion. For bodies moving through a fluid vorticity is generated at surfaces where there is a large velocity gradient. If the body is suitably shaped and placed at an appropriate angle in the fluid more vorticity may be generated on one side (upper) than the other (lower), leading to a net circulation round the body and the deflection of the flow behind the body from the flight-path direction. A lift force is thus generated having a magnitude equal to the corresponding change in momentum of the flow normal to the flight path. For wing-like shapes the vorticity is shed from the trailing edge as a sheet across the span. This sheet rolls up downstream of the object to form two trailing vortices.

Implicit with the production of lift in this manner is the supply of kinetic energy by the wing, which is achieved through work by the wing on the fluid. This implies a drag force will act on the wing. Thus the aim of the fluid dynamicist is to define a vehicle shape that minimises the overall drag while providing the required lift.

In general the necessary lift with the lowest drag is obtained when the flow is attached over the whole lifting surface, with vortices only being shed from the wing tips. This ideal is approached on wings of transport aircraft where the flight envelope is restricted to low to moderate angles of attack and to subsonic speeds below the onset of strong compressibility effects. Wings on this type of aircraft generally have low sweep and large span to generate a downwash field at the wing trailing edge having only a small contribution from the relatively weak tip vortices. Figure 1 shows two strike aircraft demonstrating this type of flow: an A10, which has an unswept wing, and a Tornado with the wing set at 25° sweep. The cores of the tip vortices can be clearly seen.

For combat air vehicles it is typically necessary to operate at higher subsonic speeds, and to go beyond moderate angles of attack, to meet military requirements. Under these conditions a wing with low sweep will produce the disorderly flow separation described above. This not only gives a large increase in drag but also introduces strong unsteadiness into the flow. The latter can produce buffeting of the airframe, which cannot be tolerated because of the resulting increase in structural loads, and dynamic characteristics of the vehicle that may render it difficult or impossible to control. The disorderly flow generated is illustrated in figure 2, which shows an F-18 research aircraft fitted with tufts on the upper surface of the wing: the random directions of the tufts on forward part of the wing indicate the degree of disorder in the flow separation.

To avoid the onset of this type of flow separation other vehicle features are introduced to generate lift in a controlled manner up to the limits of the flight envelope required. Sweeping the lifting surfaces causes spanwise flow which, beyond moderate angles of attack, leads to the production of leading-edge vortices. Low to moderate angles of wing sweep (less than about 55°) may be unsatisfactory as the formation and structure of leading-edge vortex flows from the rounded edges typically used on subsonic / transonic aircraft is very sensitive to surface conditions, scale effects (Reynolds no), and speed (Mach no.).

Higher sweep angles produce strong, stable vortex flows, for example the Lightning shown in figure 3. As a result a larger proportion of the lift required in manoeuvre is produced by the vortices on the upper wing surface, but the drag associated with the lift generated is also higher. This leads to penalties in mission performance which are generally unacceptable for a combat aircraft operating largely in the subsonic and transonic speed regimes. Thus other means have to be sought for generating lift and ensuring the consistent onset of vortex flow on wings of moderate sweep. Some of the many approaches that have been used on fighter aircraft are shown in figure 4:

(a) vortex generators, on a Buccaneer strike aircraft
(b) saw teeth shown on an F-4 Phantom
(c) strakes or leading-edge root extensions (LERX), on an F-16 (and also on F-18 in figure 2).
(d) foreplanes on Rafale

In each case it can be seen that these features produce a vortex system. The vortex systems restrict the growth of the regions of disorderly separated flow as the angle of attack is increased. Some additional lift is produced directly by these vortices but more importantly they allow the vehicle to be flown in a controlled manner to higher angles of attack, which can produce additional lift.

For short-range weapons there is less concern about efficiency of flight; the flow over the fin of a Mk82 bomb shown in fig 5 is dominated by leading edge and tip vortices.

For rotary-wing vehicles the magnitude of the maximum lift available from the rotor determines the boundaries of the flight envelope. Because of the need to trim the vehicle in roll the maximum usable lift is determined by the maximum lift that can be generated on the retreating (relatively slower) blade of the rotor. This lift is limited by the onset of stall at the tip of the blade. By incorporating a swept section with a larger chord at the tip of the parallel chord blade it is possible to generate a vortex flow over the tip that maintains attached flow immediately inboard up to higher values of the local angle of attack. Development work in the UK on this concept during the 1980s led to a 15% increase in rotor lift and hence a corresponding increase in the load carrying or manoeuvre capability of the vehicle.

Control

Conventional control devices (variable incidence surfaces or hinged trailing edges on surfaces) generate forces and moments by modifying the local distribution of lift, with the flow remaining attached to the vehicle surface. Thus these devices lose their effectiveness when the flow begins to separate and alternatives may be required for flight above moderate angles of attack. This requirement for alternative devices is enhanced by the need to minimise the number and size of control surfaces that could potentially compromise the vehicle signature when deflected. Small devices that generate and manipulate the vortices over the vehicle are one means that can be used to provide additional control forces and moments. This approach is complicated by the fact that the lift produced by a vortex has a relatively long time lag and varies in a non-linear fashion with the angle of attack, in contrast to the lift produced by surfaces with attached flow which varies linearly with angle of attack. This behaviour can introduce problems in the trim and control of the vehicle.

Above moderate angles of attack, vortices are shed from the nose of the fuselage. Generation and manipulation of these vortices has been shown to be capable of providing sufficient force and moment contributions for control. Research work (e.g. that reported in CP-494) has led to full-scale demonstration of control systems based on this approach but this has not yet matured to use on operational vehicles. Unfortunately the presence of sensor apertures in the nose region of vehicles makes it very difficult to integrate devices for vortex flow manipulation in this region. In the example shown in figure 6 an F-18 was fitted with hinged, retractable strakes on the nose to produce lateral forces for control. Alternative schemes employ blowing or sucking of air in the region close to the tip of the nose.

The effectiveness of conventional means of control can be extended to higher angles of attack by the appropriate use of vortex flows. An example is the auxiliary tail surface on Hawk, shown in fig 7. This is positioned immediately upstream and below the leading-edge of the tailplane. It comprises a highly swept wing, similar to a strake, mounted parallel to the fuselage axis. At high angles of attack this surface generates a vortex flow that interacts with the flow over the upper surface of the tailplane and delays the onset of tailplane stall.

Drag reduction

A problem in providing convergent to divergent nozzle geometry for engines with reheat is to define external lines to minimise drag and nozzle mass while retaining a long life for the nozzle immersed in the engine-reheat environment. Several combat aircraft have shed nozzle “petals’ or have had nozzle petals with an unacceptably short life. The nozzle outer petals on EF2000 (figure 8) produce triangular planform cavities with the apex forward, when in the reheat configuration. The design aim for this geometry was to improve the cooling of the inner and outer petals and thus reduce weight through the use of lighter lower-temperature materials. Additional benefits were achieved as this nozzle design was developed using large-scale models. Measurements indicated that the cavity between the inner and outer nozzle petals was being pressurised by the external flow. It was deduced that this was caused by vortices generated by the highly swept edges of the petals when in the reheat condition. This produced further benefits:

- It re-energised the external flow over the rear of the fuselage so that this flow remained attached and afterbody drag was minimised. Model measurements indicated a 10% reduction in zero-lift drag, and a corresponding increase in vehicle performance.
- It suppressed a large part of the unsteady flow feedback effect from the jet (screech), which could have imposed unacceptably large unsteady loads on the petals.

Internal flows

Combustion chambers on jet engines make extensive use of vortex flows to achieve more efficient combustion and improved surface cooling to permit increases in operating temperature. For example air diffused from the compressor is rapidly expanded and turned in a ‘dump diffuser’ which features a vortex ring that stabilises the flow and ensures uniform air distribution round the engine circumference. The fuel injector features an offset cross arm so that the flow generates an internal vortex that ensures the whole of the internal surface is scrubbed, and hence adequately cooled. In the traditional vaporiser (fig 9a) the central entry jet flow produces a toroidal recirculating vortex that stabilises the combustion. The next generation of combustion chambers (fig 9b) incorporate an air swirler (fixed vanes in an annulus) which generates a longitudinal vortex flow and an adverse pressure gradient in the chamber. This pressure gradient causes some of the hot combustion products to be recirculated back to the incoming mixture. The result is better combustion with higher temperatures and greater efficiency. This type of combustor gives better control of emissions (e.g. smoke) and hence improved vehicle survivability, however it is difficult with this design to match the air and fuel flow requirements to give good combustion and low emissions across the throttle range. To meet this need novel types of fuel injector have been proposed. For example by using fluidic control of the direction of the air jets that leave the air swirler, the strength of the longitudinal vortex may be controlled and matched to the fuel / air requirements at a particular throttle setting in order to minimise emissions.

The internal walls of the combustion chamber are cooled by air injected parallel to the walls near the surfaces. Sharp corners are used on the rearward facing ramps through which the cooling air is injected into the combustion chamber. These corners generate cross-stream vortices that ensure the cooling flow stays attached to the wall, thus preventing melting or burning of the chamber.

Ships and submarines

In general the approach followed by the hydrodynamicist is to rely as far as possible on buoyancy and propulsive forces to provide lift and control, aiming to minimise the occurrence of vortex flows because of the penalties in performance and survivability that they bring.

Vortex flows that must be ameliorated

Body vortices

The flow over a round body at moderate to high angles of attack separates from the smooth surface in an asymmetric manner. If we consider first the blunt-nosed body typical of submarines, the flow remains attached on the front part of the body but at moderate to high angles of attack asymmetric vortex separations occur toward the rear of the body. Fig 10 shows total pressure contours from a CFD simulation of the flow over a submarine hull. The vortices generate lateral forces and moments that can produce un-commanded lateral motion. In a turning manoeuvre the vortex generated by the sail interacts with the flow over the body to produce an asymmetric vortex flow that can generate pitch and heave motions of the submarine. Furthermore the drag associated with the vortices can produce penalties on turn performance. The vortex separations can also impinge on the propulsor downstream, leading to a loss in performance. All the vortices generated potentially enlarge the size of the wake left by the submarine and hence can compromise survivability.

On combat aircraft, which typically have pointed noses to reduce high-speed drag, the onset of flow separation occurs further forward on the body. Progressing from the nose of the body aft a vortex is shed first from one side and then the other. The stable asymmetric vortex system that results downstream induces a significant lateral force on the nose of the aircraft that can cause un-commanded lateral motion (nose slice). The side from which the first vortex is shed is determined by very minor asymmetries in the tip geometry of the nose of the body. The asymmetric behaviour may be removed by symmetrical sharp

edges in the nose region of the body, as illustrated in figure 11 which shows the small nose strakes on Mig-29.

Wing vortices

The system of vortices designed to generate lift over the required flight envelope can be strongly influenced by lateral motion. In particular the angle of attack at which the position of the breakdown of the vortices moves forward of the wing trailing edge varies with yaw angle. Thus the flow over the aircraft can become very asymmetric under sideslip conditions. The breakdown of the vortex above a wing can produce a loss of lift on that wing and an uncommanded motion in roll. Figure 12 shows the vortices on an F-16 executing a sideslip to port. The breakdown of the port vortex has moved upstream and occurs above the port wing while that on the starboard side breaks down aft of the wing trailing edge. To avoid problems in stability and control it is necessary to ensure that the breakdown of the main wing vortices does not occur above the wing within the desired flight envelope. This is generally achieved by appropriate tailoring of the lift-generating vortex system, but the phenomenon does in many cases set the limit for controllable flight. Figure 13 shows the vortex flows and the variation of the lateral stability derivative $C_{l\beta}$ (rolling moment due to sideslip) with increase in angle of attack, for a canard configuration sideslipping to starboard. Moving anticlockwise round this figure from the top left, the first view has similar vortex flows over both wings, but with more lift being generated from the windward (effectively lower sweep) wing and hence producing a stable (negative) value of $C_{l\beta}$. In the second view vortex breakdown has moved forward over the windward wing so limiting further lift generation on that wing. In the third view the vortex breakdown on the starboard wing has moved further upstream leading to further lift loss and an unstable value of $C_{l\beta}$. In the fourth view the difference in lift between the wings, and hence the roll instability, has reached a maximum. Beyond this point vortex breakdown moves forward of the trailing edge for the leeward wing, and the corresponding lift loss leads to a stable value of $C_{l\beta}$. While it is possible for flight control systems to provide artificial stability it is far more difficult to handle rapid changes of stability of the type illustrated in fig 13.

Junction effects.

The junction between a cylinder and a surface generates a horseshoe shaped vortex as shown in fig 14. On an air vehicle this type of flow in the junction between a wing and a body leads to a loss of lift and an increase in drag. Local surface shaping in this region to blend the wing and fuselage together can greatly reduce the strength of the junction vortex, and hence reduce the loss in performance. Removing this discontinuity between the wing and body also has a favourable effect on radar signature.

Within turbomachinery this type of flow in the junction between a blade and the hub wall of the engine will produce a corner vortex that will travel through the engine. By appropriate shaping of the blade planform and the surface in the hub area this rotary flow may be harnessed to improve the mixing of the flow over the hub surface. Component efficiencies can thus be improved and cooling requirements reduced or higher temperatures employed, all contributing to improved engine performance or lower engine weight.

Chine vortices

Strakes extending from the wing apex or at the nose of the body have been cited as means of controlling vortex-flow development downstream. Most low-signature aircraft (such as F-22 shown in fig 15) have sloping sides with a sharp edge or ‘chine’, running along either side of the forebody. This generally has a similar effect to a strake but, because the chines are very highly swept, vortex flow is produced at low angles of attack. Thus while chines may be effective in controlling the vortex flow over the wing and body at positive angles of attack, the effect of the chines also needs to be considered when the aircraft is flying at negative angles of attack. As can be appreciated from figure 15 it is necessary to ensure that separated flow on the underside of chines does not have an adverse effect on the engine intake performance.

Intake lips and diverters
Vortices may be shed from the lips of engine intakes or their boundary-layer diverters as is evident on the F-4 Phantom shown figure 16. While vortices from this source may not be large they can interfere with the wing flow and are likely to have an adverse effect on aircraft performance as a result of the associated contribution to drag.

Ground vortices
The air flow approaching an engine intake or propeller of an air vehicle which is stationary or moving slowly on the ground can develop into vortex before being ingested by the intake or propeller. An example is shown in figure 17 for a C-130. Because the vortex can pick up small objects remote from the aircraft it is essential that standing areas and taxiways are regularly inspected, particularly for areas where static engine tests are to be done.

Vortex Wakes
The vortices generated by an air or sea vehicle persist for a large distance behind the vehicle. Significant velocity perturbations can be encountered, in particular those associated with the wing-tip vortices. This effect can be ameliorated by applying operating procedures that prevent other vehicles from encountering the wakes of preceding air vehicles e.g. for flight refuelling, and during landing. Of more importance to military operations is the fact that the reduced pressure near the core of wing tip vortices may lead to the condensation of water particles to form visible contrails, with a consequent reduction in survivability in hostile airspace. Weakening the vortices will delay the formation of contrails to higher altitudes.
Sharp edges on the superstructure of ships or the flight deck on aircraft carriers generate vortex-type separations that have a strong impact on the operating environment for maritime air vehicles. For rotorcraft detailed knowledge of these flows is essential to define a safe envelope for ship-based operation.
Rather than avoiding wake vortices it is actually possible for following air vehicles to make use of them to increase performance. Birds fly in V formation so that the upwash produced outboard of the wing tip vortices of the leading member can be used to reduce the lift that it is necessary for the following members in the V to generate. Until recently this approach could not have been contemplated for the routine operation of man-made vehicles because of the magnitude of the piloting task. In 1995 work at TU Braunschweig and DLR demonstrated an automatic control system on a Do-28 aircraft following a Do-228. By harnessing a GPS-based automatic position-control system, research work at NASA on a pair of F-18 aircraft is investigating the practicality of this approach for high-performance military air vehicles. It is estimated that the following aircraft may benefit by 10% -15% in terms of drag and fuel reduction.
Turning our attention to the potential negative effects of vortex-ring wakes, fig 18 shows the vortices generated by a C-130, illustrating the potential effect on the air drop environment if the aircraft departs from unyawed flight. A submarine example is illustrated in the ‘Crashback’ manoeuvre simulation shown in fig 19. The objective here is to bring the submarine to rest as fast as possible by reversing the propulsor rotation. An enormous ring vortex is developed which passes forward over the submarine hull interacting with it to produce potentially out-of-plane forces and hence an unpredictable trajectory for the submarine.

Unforeseen vortex flows or vortex flow consequences

Fin buffet
While the effect on aircraft stability of vortex breakdown occurring above aircraft wings has been understood for several decades it was only in the 1980s that major and unexpected effects on aircraft loads were encountered. Fig 20 shows that at moderate angle of attack vortex breakdown occurs immediately upstream of the twin fins on F-18. The resulting unsteady flow provides the aerodynamic excitation to cause buffeting of the fins. These unsteady aerodynamic loads reduce fin structural life markedly if the operational use of the aircraft involves substantial time in manoeuvre. Because of the complexity of the vortex flow development, breakdown and interaction with the aircraft structure, simulation has still not reached a state where these effects can be reliably predicted. As a result, in

common with many other of the effects cited in this paper, reliance has to be placed on experimental work, preferably at full-scale conditions, to understand this phenomenon.

Rear fuselages vortex separations
The back ends of tactical transport aircraft are typically designed with upsweep on the under surface of the fuselage to accommodate a large loading ramp and an airdrop capability for large items. On these aircraft the design aim is to maintain attached flow over the fuselage for the normal operating envelope. There have been several instances where flight testing has shown that this was not achieved. Flow can separate and form a vortex from the side edges adjacent to the loading ramp. The resulting large-scale vortex wake downstream increases aircraft drag and thus reduces range performance. Furthermore the resulting aircraft environment for airdrop may not be acceptable in terms of precision and safety. In some cases strakes have been fitted to the side edges adjacent to the loading ramp to tailor the vortex separation to increase the extent of attached flow on the rear fuselage.

Failure cases
As an example of unexpected vortex effects fig 21 shows the flow over the upper surface of an F-18 wing when a leading-edge flap actuator failed on the starboard wing, resulting in an upward flap deflection of 15°. Instead of this destroying lift as might be expected and the aircraft rolling to the right, a vortex flow was formed which initially generated additional lift and caused a roll to the left.

Rotorcraft
Because of the very complex vortex wake shed by the rotor, as illustrated in fig 22 for Apache, the tail surfaces on rotorcraft operate in a very non-uniform environment that changes markedly during flight. There are particularly large variations in the onset flow during the transition between hover and forward flight. There have been several instances where very major changes in the configuration of tailplanes have had to be made late in the flight-test stage of development to provide adequate stability and control.

Vehicle build quality and in-service degradation
In previous sections the sensitivity of vortex-flow development to details of vehicle geometry has been noted, particularly for wings and separations from smooth surfaces. While many regions of an air vehicle produce a flow that is insensitive to minor shape changes, steps or gaps, the flow in some areas can change radically if the shape departs from that designed. Thus it is essential to identify these areas and then apply targeted inspection and monitoring throughout the operational life of the vehicle. While it is a reasonable design aim for the aerodynamicist to reduce or eliminate critical dependencies on shape, current design drivers for survivability limit the extent to which this can be achieved.

Sea vehicles
While no specific examples of unexpected effects of vortex flow may be quoted for sea vehicles, it is likely that this is because the topic has not, until recently, been the focus of attention. It is probable that some phenomena encountered on sea vehicles may involve vortex flow effects as yet unidentified.

Future Military Vehicles

A large part of the previous discussion has focused on vehicles that have been in service for many years, and there has been an emphasis on manoeuvrability at moderate to high angles of attack. Some configuration trends for future air vehicles may be noted from the open literature (fig 23):

- moderate to high sweep of all surfaces, generating complex vortex flows
- sharper leading-edges to lifting surfaces, leading to the early onset of vortex flows
- bodies with edges (e.g. chines) producing additional vortices. These are typically generated in forward regions on the vehicle so they will potentially interact with all the downstream vortices generated by the lift and control surfaces.
- increased blending between wing and body, effectively increasing wing thickness and thus increasing the likelihood of complex shock-wave / vortex separations at high speed.

Future surface ships will be likely to feature hull sides that slope inboard above the waterline, which will have an effect on stability, and a sleeker topside, which will have an effect on the operating environment for rotor craft.

Concluding Remarks

General

(1) A knowledge and understanding of vortex flows and flow at high angle of attack will continue to be of central importance in the development of military air and sea vehicles. The present overview has indicated the complexity of the flows and the magnitude of the task involved in gaining the necessary understanding.
(2) The predictive capability for vortex flows remains inadequate for military air and sea vehicles. Some problems are still major research challenges, while for others research has demonstrated potential means for solution but the technology still needs to be matured to a level where industry can use it in design.
(3) While the historical knowledge of vortex flows accumulated by aerodynamicists and hydrodynamicists has allowed some general 'rules' to be established, it is dangerous to assume that because there are geometric similarities with an existing configuration that all the important flow features for a new configuration are understood.
(4) The emphasis on survivability is producing new vehicle shapes, so there is an increased likelihood that an important interaction effect will be missed at the design stage. Hence targeted configuration research remains essential to reduce the risk of shortfall in operational performance.

Specifics

From this broad introduction to the topic of military vortices some more specific comments may be made:
(1) Computational methods for the prediction of interacting vortex flows are not yet fully proven. Tools to allow the rapid computation of vortex flows about complex configurations are still at the research stage. Several aspects of simulation continue to need attention:

- Modelling the onset of vortex flow from boundary-layer separation on smooth surfaces
- Prediction of vortex breakdown for complex vehicle configurations
- Scale, compressibility and unsteady effects

(2) Experimental tools also have limitations. Because of the sensitivity of vortex flow development and vortex interactions to the local environment, a wind-tunnel simulation can be unrepresentative. In particular scale and interference effects may be significant.
(3) Vortex interaction effects need more attention across disciplines.

Acknowledgements and References

The author is grateful for discussion and images from:
J Campbell and J Chambers, NASA Langley (figs 1-4, 12, 16-18; ref *Patterns in the Sky* NASA SP-514 Langley Research Centre 1994), D Thompson, AMRL (figs 5, 20, 21), S Lang, BAE Systems (fig 7), P Martin, dstl (fig 8), C Wilson, QinetiQ (fig 9), P Purtell, ONR (figs 10, 19), E Kraemer, EDS (fig 13), J Gorski, NSWC (fig 14), A Jones, QinetiQ (fig 22)

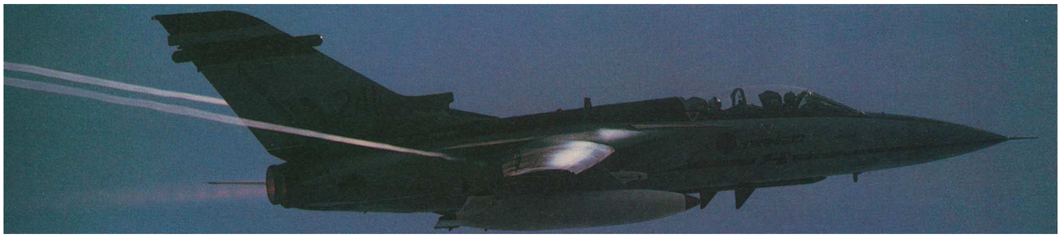


Fig 1 Tip vortices on wings having low sweep: A10 and Tornado

Fig 2 Disorderly flow separation on the upper wing surface of F-18

Fig 3 Vortex flow over 60° sweep wing of Lightning

(a) Vortex generators on Buccaneer

(b) Saw teeth on F-4

(c) Strakes on F-16

(d) Foreplanes on Rafale

Fig 4 Vortex generation on wings of moderate sweep

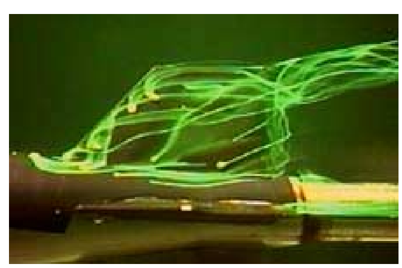


Fig 5 Flow over fin of Mk 82 bomb

Fig 6 Mechanical strakes on F-18 nose

Fig 7Auxiliary tail surface on Hawk

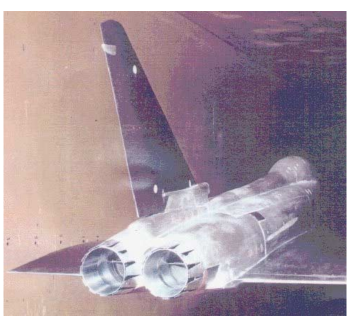
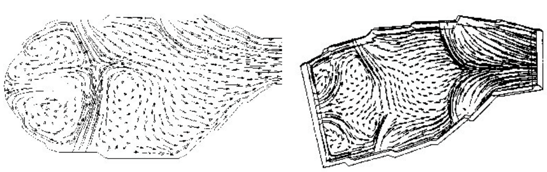


Fig 8 Nozzles on EF2000



(a) vaporiser type *(b) airspray type*

Fig 9 Combustion chamber internal flows

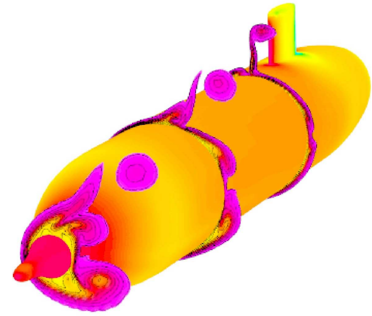


Fig 10 Vortex flow on manoeuvring submarine

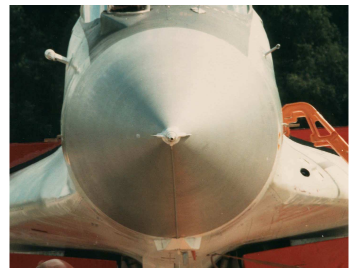


Fig 11 Nose strakes on Mig-29

Fig 12 Asymmetric vortices on F-16 in sideslip

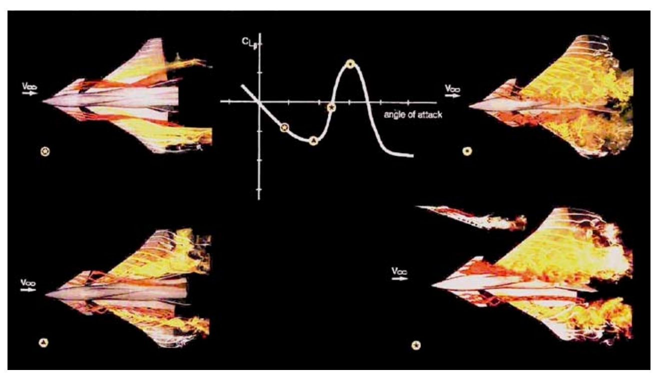


Fig 13 Lateral instability due to asymmetric vortex bursting

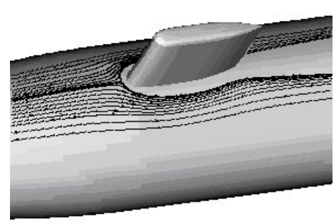


Fig 14 Horseshoe vortex formed at wing-body junction

Fig 15 Fuselage chine on F-22

Fig 16 Vortex from intake diverter on F-4

Fig 17 Ground vortex generated by C-130

Fig 18 Vortices from C-130 propellers

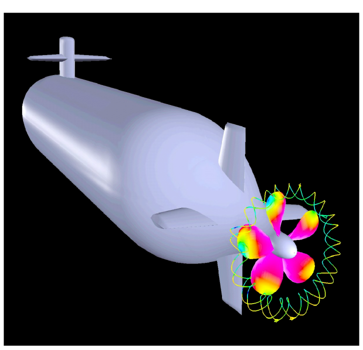


Fig 19 Simulation of crashback manoeuvre

Fig 20 Impact of burst vortices on F-18 fins

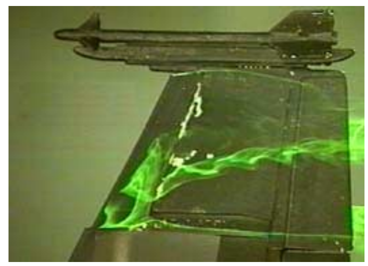


Fig 21 Vortex flow generated by F-18 flap failure

Fig 22 Rotor flow field from Apache

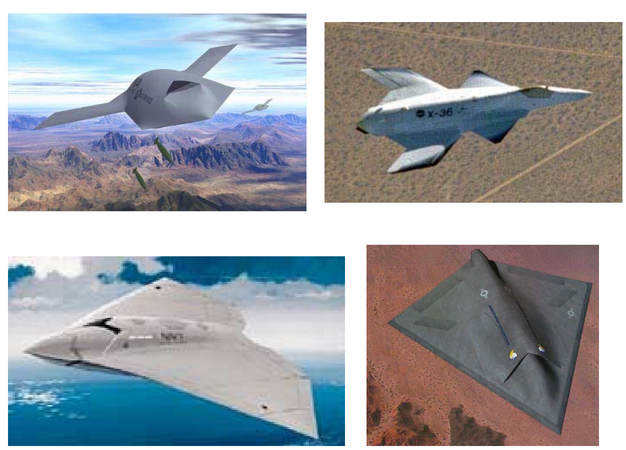


Fig 23 Future air vehicle configurations